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THE APPLICATION OF ERTS IMAGERY TO MAPPING SNOW COVER IN THE WESTERN UNITED STATES: SUPPLEMENTAL REPORT

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SUPPLEMENT TO THE FINAL REPORT For Period June 1974 thru January 1975

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prepared for
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16. Abstract A supplemental study of the application of ERTS-1 data to mapping snow cover in mountain regions of the western United States and flatter terrain areas of the Mid-west is conducted. The extent of snow cover is mapped for selected mountain regions using data from the 1973 winter and summer seasons; comparative analyses are performed using data from corresponding wintertime periods of 1973 and 1974; and a quantitative correlation between observed snow cover depletion and resulting runoff is presented for one test area. Analyses of snow cover extent over the flatter terrain areas of the Mid-west are performed for the 1973 winter and spring seasons. The additional analyses performed under this supplemental study further substantiate the application of ERTS imagery to mapping snow cover. Limited snow cover restricted to higher elevation ridges of the southern Sierra Nevada during the 1973 summer season can be identified. Comparative analyses performed using data from corresponding wintertime periods of 1973 and 1974, viewing the southern Sierras and central Arizona mountains, indicate that although small differences in areal snow extent can be mapped, differences in the snowpack volume are not obvious. The combined use of visible and near-IR data viewing the Cascades provides further evidence for distinguishing areas of presumably wet, melting snow surfaces.					
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PREFACE

In a supplemental study of the application of ERTS-1 data for mapping snow cover, snow is mapped for selected mountain areas of the western United States using data from the 1973 winter and summer seasons; comparative analyses are performed using data from corresponding wintertime periods of 1973 and 1974; a quantitative correlation between observed snow cover depletion and resulting runoff is presented for one test area; and analyses of snow cover extent over the flatter terrain areas of the Midwest are performed for the 1973 winter and summer seasons. Additional comparisons of the ERTS data with high altitude aircraft, as well as Skylab, photography have also been conducted.

The additional analyses performed under this supplemental study further substantiate the application of ERTS imagery for mapping snow. Limited snow cover restricted to higher elevation ridges of the southern Sierra Nevada during the 1973 summer season can be identified. Comparative analyses performed using data from corresponding wintertime periods of 1973 and 1974, viewing the southern Sierras and central Arizona mountains, indicate that although small differences in areal snow extent can be mapped, differences in the snowpack volume are not obvious. The combined use of visible and near-IR data viewing the Cascades provides further evidence for distinguishing areas of presumably wet, melting snow surfaces.

The reprocessing of imagery to a larger scale alleviating shadow and forest effects in the Upper Columbia Basin is also discussed. Comparisons of the ERTS data with high-altitude aircraft and Skylab photography provide further evidence that major features including boundaries of the areas of significant snow cover can be mapped as accurately from ERTS imagery as from the higher resolution data from the aircraft. A comparative analysis of the snow cover depletion of four southern Sierras river basins with actual runoff data during the 1973 spring season shows good correlation during the period of maximum runoff. Also, the analysis and interpretation of ERTS imagery viewing the flatter terrain areas of the Midwest reveals a number of interesting features.

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1. INTRODUCTION

1.1 Results of Initial Investigation

The work reported herein represents a continuation of an investigation to evaluate the application of ERTS-1 imagery to mapping snow cover in the mountainous areas of the western United States and over relatively flat terrain areas of the north-central part of the country. The results of the initial investigation have been presented in an earlier report by Barnes, Bowley and Simmes (1974), as well as in papers at the Second and Third ERTS-1 Symposia (Barnes and Bowley, 1973; and Barnes, Bowley and Simmes, 1973). In the initial investigation, data were analyzed for two primary western mountain sites: the southern Sierra Nevada in California and the Salt-Verde Watershed located in the central Arizona mountains. The data sample was from the late summer and early fall of 1972 and the winter, spring and early summer of 1973.

The results of the initial investigation have shown that the amount of information in ERTS imagery with practical application to snow mapping is substantial. The results of analysis of ERTS imagery for the Arizona and California test sites indicated that the extent of the mountain snowpacks can be mapped from ERTS data in more detail than is depicted in aerial snow charts; in four river basins of the southern Sierra Nevada, the difference between the percentage of the basin snow covered as measured from ERTS and from aerial survey charts was of the order of only 5 percent for all cases except one. Moreover, for the Sierras and Salt-Verde test sites, the amount of useful data that could be obtained indicates that cloud obscuration is not a serious deterrent to the use of satellite observations for snow survey.

In addition to comparative analysis with aerial snow charts, the ERTS imagery has also been compared with high-altitude aircraft photography. The results of the comparative analysis indicated that although small details in the snow line that cannot be detected in the ERTS data can be mapped from the higher-resolution aircraft data, the boundaries of the areas of significant snow cover can be mapped as accurately from the ERTS images as from the aircraft photographs. There was also evidence that the combined use of visible and near-IR imagery may have application for distinguishing areas of melting snow.

1.2 Purpose of Supplemental Study

The purpose of the supplemental study was primarily to analyze additional ERTS-1 imagery collected during the late spring and summer 1973 over the mountain areas of the western United States and collected during the 1972-1973 winter season over relatively flat terrain areas of the north-central part of the country. Additional tasks to be undertaken included:

- (1) Analysis of ERTS-1 data from the 1973-1974 fall and winter season for comparison with snow cover distributions observed during corresponding time periods of the previous year;
- (2) Correlate ERTS imagery with additional ground-truth information including available Skylab photography; and
- (3) Establishment of quantitative correlation between observed snow cover depletion and resulting runoff in at least one test area.

Analysis of additional ERTS imagery for the 1973 summer season was conducted for the areas of the southern Sierra Nevada and the Cascades. Observations showing apparent snow cover restricted to higher elevation ridges of the Sierras, an example of the combined use of the visible and near-IR data for distinguishing areas of presumably wet, melting snow surfaces in the Cascades, and an example of reprocessed imagery to a larger scale alleviating shadow and forest effect are discussed in Section 2 of this report. Also presented in Section 2 are important features which are revealed in the analysis and interpretation of a number of ERTS images viewing the flatter terrain areas of the Mid-west. These include: (1) variations of reflectance with snow depth; (2) rapid snowmelt; (3) the enhancement of geological features with snow on the ground; (4) the minimum amount of snow accumulation that can be detected in ERTS imagery; (5) the effect of relatively insignificant snow accumulations on the genesis of low level convective cloud layers; and (6) apparent discrepancies in ground truth reports of snow depth during times of rapid melting.

ERTS-1 has been in operation since late July 1972. Therefore, it was possible to analyze snow cover distributions over the western mountain test sites for corresponding time periods during two winter seasons (1972-1973 and 1973-1974). Discussion of snow cover distributions in the southern Sierras for February 1973 and 1974 and in the Salt-Verde Watershed (Arizona) for January 1973 and 1974 are presented in Section 3.

In the initial investigation, ERTS imagery was compared with aerial survey snow charts and a sample of aircraft photographs. In the supplemental study, ERTS imagery viewing a portion of the Salt-Verde Watershed was compared with Skylab, as well as aircraft photographs. The comparative analysis is presented in Section 4. Additionally, one objective of the study was to demonstrate the correlation between observed snow cover depletion and resulting runoff for at least one river basin. The percentage of snow cover during spring and early summer 1973 as determined by ERTS for the four southern Sierras river basins (Kings, Kaweah, Tule and Kern), compared to actual runoff data obtained from the state of California, Department of Water Resources is discussed in Section 5.

This supplemental report is intended to provide additional examples demonstrating the application of ERTS imagery for detecting and mapping snow cover. Discussions of the characteristics of the ERTS system, the techniques to identify snow and to distinguish snow from clouds, and the analysis methods to map snow are presented in detail in the initial report (Barnes, Bowley and Simmes, 1974).

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2. ANALYSIS OF ADDITIONAL 1973 DATA

2.1 Sierra Nevada

Analysis of ERTS MSS-5 images of 19 July and 24 August 1973 (Figures 2-1 and 2-2) reveals subtle tonal differences along most higher elevation ridges (above about 3500m) of the southern Sierras, from near Mono Lake south to the Kings River Basin. On the earlier date, snow is evident in those specific areas indicated in Figure 2-1 which display a more uniform texture and higher reflectance than on the later date. The outer boundaries of the areas of overall increased reflectance however, agreed remarkably well with the August data.

In the initial study, data of 16 September 1972 viewing this same region was presented in both black and white and in a color composite. Examination of both types of photographs showed that some areas appearing similar to continuous snow cover in the black and white imagery were found to consist of mostly snow-free, highly reflective rock surfaces from the color imagery. Comparison of the August image with the September data of the previous year shows an obvious similarity in overall reflectance and extent of the brighter terrain, indicating that the August image is also viewing mostly snow-free, rock surfaces. Moreover, since the outer boundary of the area of overall higher reflectance in the July image is generally in good agreement with the outer boundaries observed in August, much of the higher elevation terrain is apparently also snow-free even by mid-July.

These images illustrate that positive identification and mapping of small areal extents of snow cover becomes extremely difficult during periods of higher sun angles because the reflectance of the rock surfaces closely approaches that of snow cover. Only by careful comparison of the isolated areas showing smooth, uniform texture and maximum reflectance in the July image, with the obvious changes that had occurred some five weeks later, was it possible to interpret the snow cover confined to the higher elevations.

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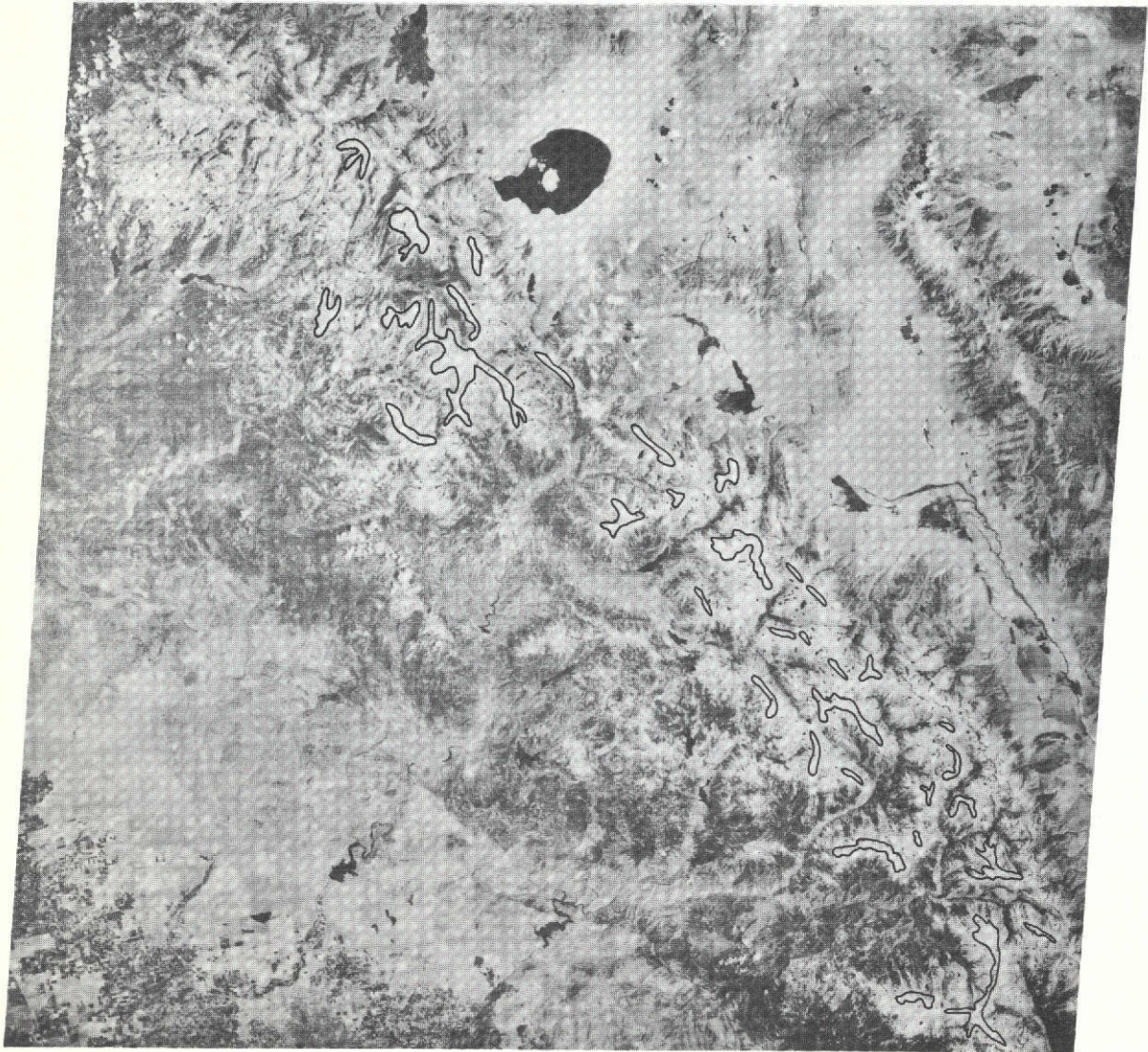


Figure 2-1 ERTS-1 MSS-5 image (ID No. 1361-18060) showing southern Sierra Nevada, 19 July 1973. Snow cover restricted to higher elevation ridges is outlined.

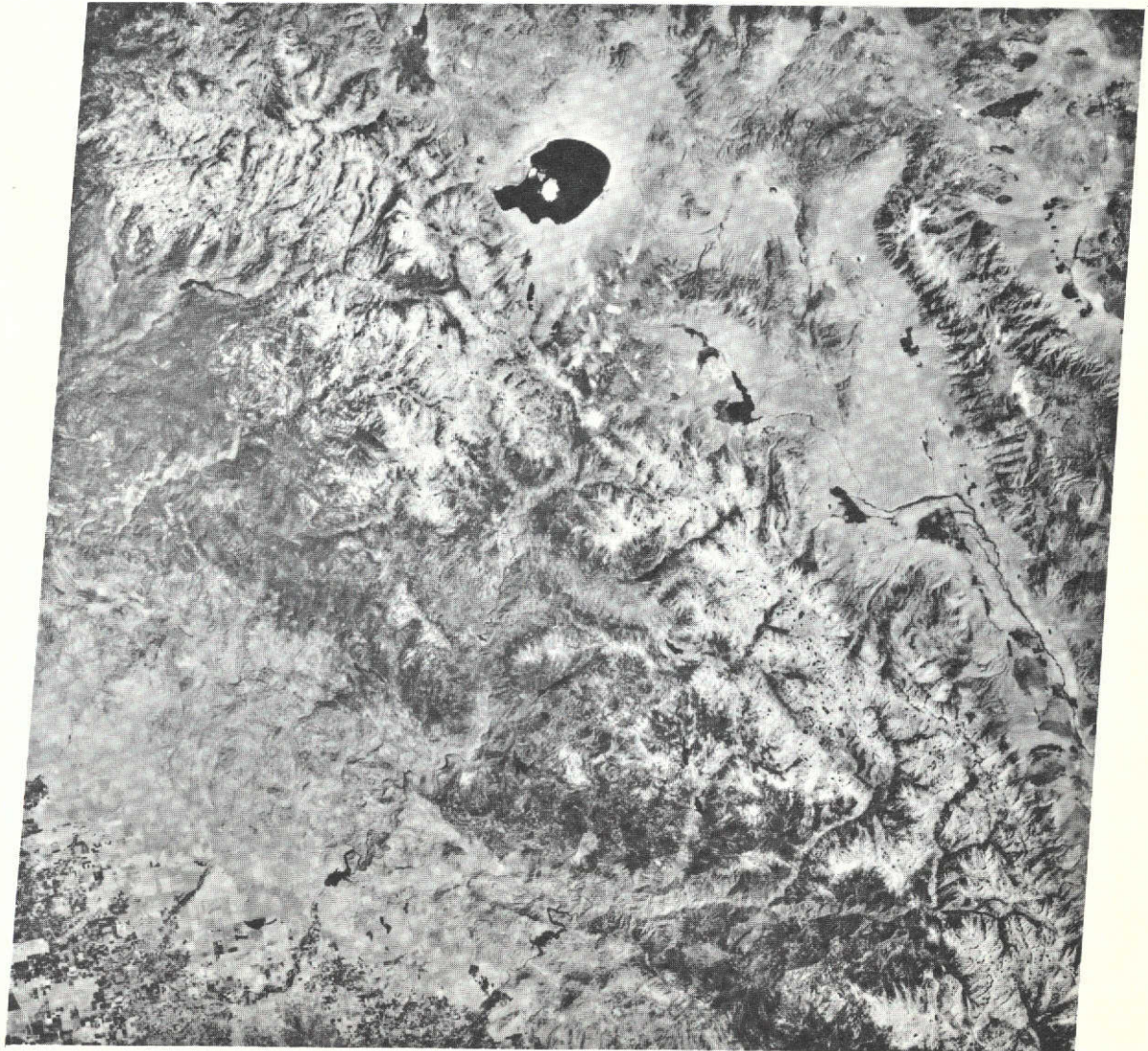


Figure 2-2 ERTS-1 MSS-5 image (ID No. 1397-18053) showing southern Sierra Nevada, 24 August 1973. Areas that were outlined as being snow covered in the previous figure now display a darker tone and less uniform texture.

2.2 Cascades

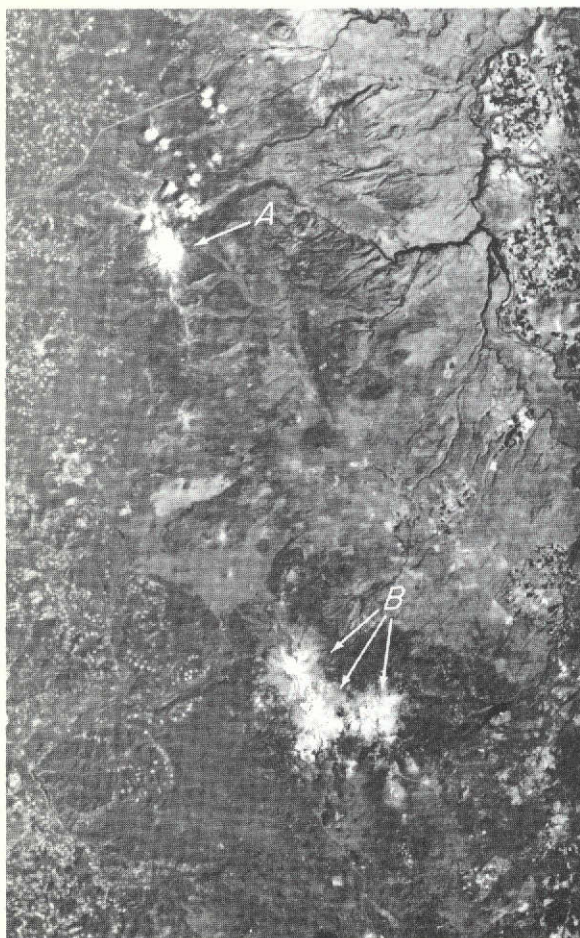
Examination of ERTS visible (MSS-5) and near-IR (MSS-7) imagery of late spring and summer has shown, in a number of instances, that areas of snow cover appearing bright in MSS-5 are considerably larger than those appearing bright in MSS-7. The lower reflectance in the near-IR has been attributed to the presence of a wet snow surface. Another example of the combined use of the visible and near-IR ERTS data for distinguishing areas of presumably wet, melting snow surfaces is shown in ERTS imagery of 28 August (Figures 2-3 a and b).

The Three Sisters mountains and Mt. Jefferson, part of the Cascade Range near central Oregon, display highly reflective snow surfaces in MSS-5 above about 2200m. Some areas of lower reflectance, indicative of snow-free rock surfaces, are also observed, such as along the western slopes of the Three Sisters. Even within the areas that appear to be snow covered in the visible band, however, the MSS-7 displays small, distinct bright patches. The locations of these bright patterns correlate closely to the locations of higher elevation glacier areas as indicated on the appropriate USGS topographic map (scale 1:250,000). In this instance, it may be that the snow remaining on the glaciers is somewhat drier than the lower elevation snow surfaces visible in the MSS-5 image.

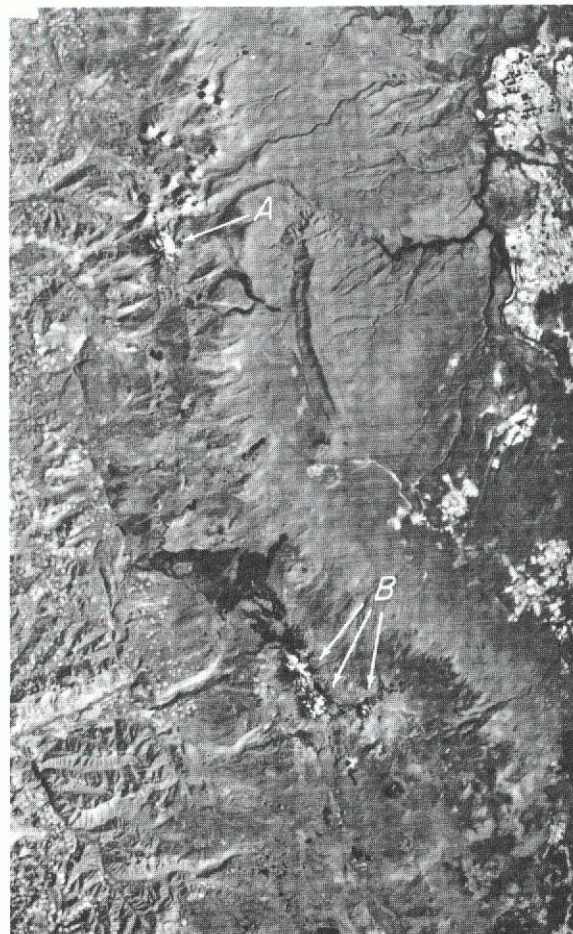
2.3 Upper Columbia Basin

In the initial study only a limited data analysis was undertaken for the Upper Columbia Basin in northern Idaho and western Montana because of the frequent cloud obscuration observed during the 1972-1973 winter season. Further examination of later ERTS images has shown that during the spring and summer of 1973 clouds also generally prevailed over most higher elevation terrain areas within this basin. Although snow extents can usually be detected in a few areas through breaks in the clouds, the overall mapping of individual mountain ranges is frequently impossible.

One unusually cloud-free MSS-5 image of 6 February (Figure 2-4) shows the extent of snow cover in the Lewis Range of northwestern Montana and the flatter terrain area immediately to the east. Although



(a)



(b)

Figure 2-3 ERTS-1 MSS-5 (left) and MSS-7 (right) images (ID No. 1401-18262) showing Mt. Jefferson (A) and the Three Sisters mountains (B) of the Cascade Range in Oregon, 28 August 1973. Note the lesser apparent snow cover in the near-IR band (MSS-7) as compared to the visible band (MSS-5).



Figure 2-4

ERTS-1 MSS-5 image (ID No. 1198-17574) viewing a portion of the Upper Columbia River Basin in western Montana, 6 February 1973. The following features are indicated: Lake McDonald (A), Hungry Horse Reservoir (B), Kalispell, Montana (C), and the Lewis Range (D). Snow depths (shown in inches, as originally reported) are also indicated. They range from 1-2 inches (3-5 cm) in the flat terrain area, and 10-48 inches (25-120 cm) in the mountainous area.



Figure 2-5 Enlargement of portion of ERTS image of 6 February 1973 shown in Figure 2-4. The following features are indicated: Lake McDonald (A), Hungry Horse Reservoir (B), Kalispell, Montana (C), Lewis Range (D), example of mountain shadows on north slopes (E), and heavily forested areas (F).

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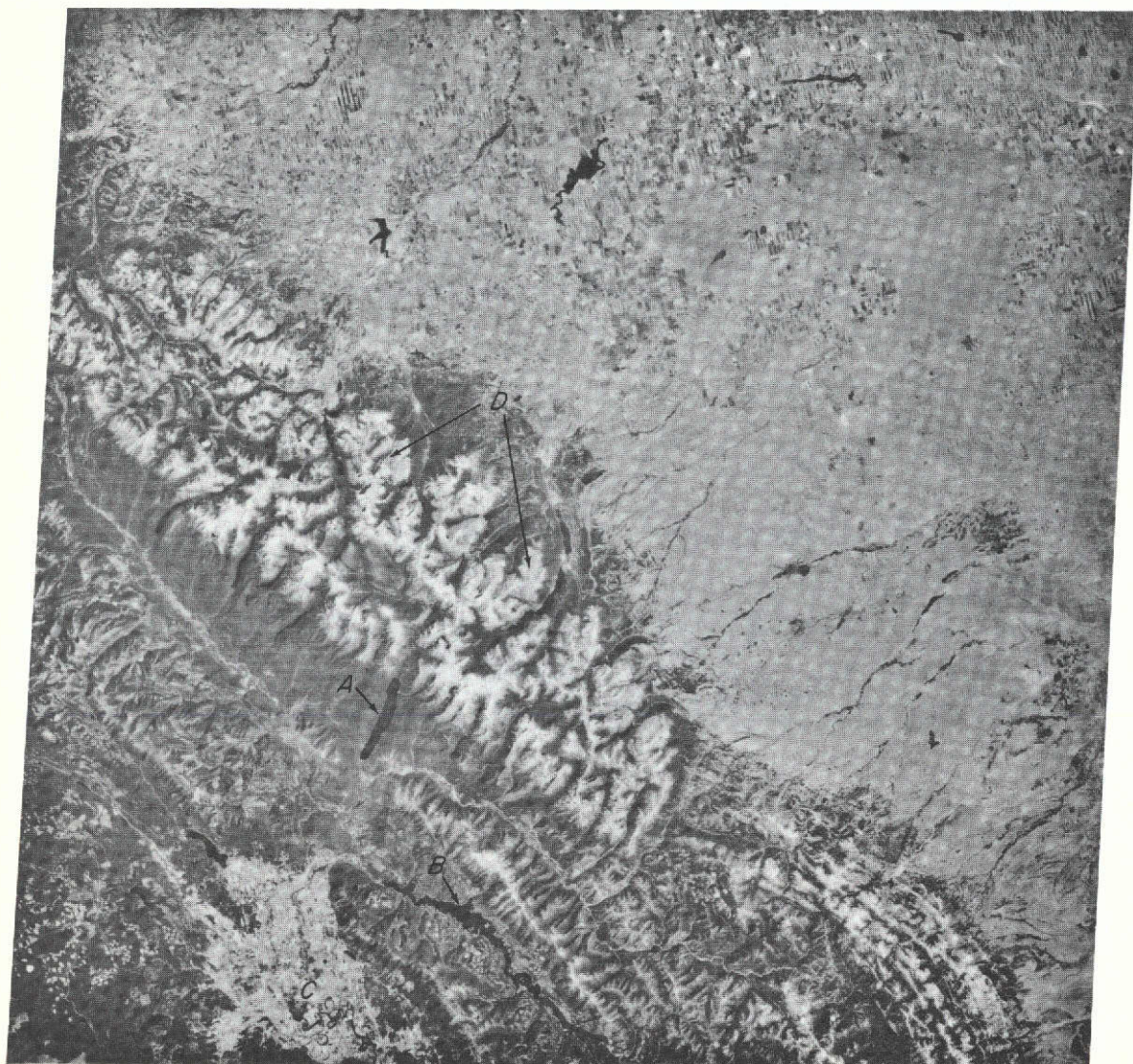


Figure 2-6 ERTS-1 MSS-5 image (ID No. 1360-17570) of 18 July 1973 showing same area of Upper Columbia River Basin viewed in Figure 2-4. The following features are indicated: Lake McDonald (A), Hungry Horse Reservoir (B), Kalispell, Montana (C), and the Lewis Range (D).

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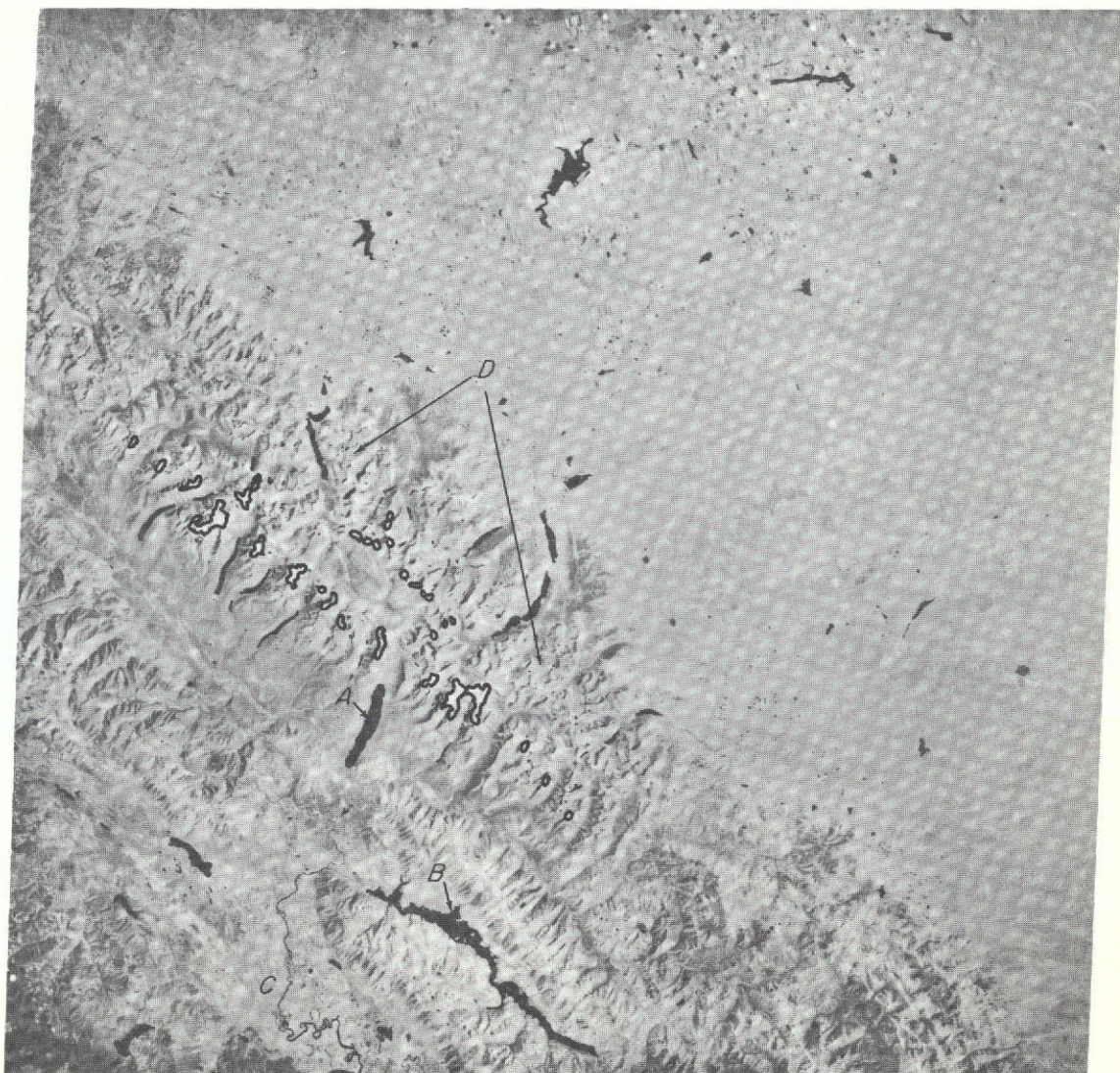


Figure 2-7

ERTS-1 MSS-6 image (ID No. 1360-17570) of 18 July 1973 showing marked reduction in reflectance within higher elevations of Lewis Range as compared to Figure 2-6. The features indicated are identified in Figure 2-6. The areas outlined have a higher reflectance and are probable snow cover.

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only a limited sample of ground truth exists for this region, as much as 125 cm of snow is reported in the higher elevations, whereas only 3-7 cm is reported in the area of flat terrain.

The combination of low sun angle (21°) creating shadows along the north facing slopes of the Lewis Range and the dense forest cover at lower elevations makes precise snow mapping difficult at this standard scale. The shadow problem and forest effect can be alleviated somewhat by reprocessing this portion of the image (using the original 70 mm negative) to a larger scale (Figure 2-5) and using a slightly longer exposure time. Snow-free terrain within the shadowed slopes and heavily forested terrain is now discernable and the actual snow extent can be more easily mapped.

ERTS visible imagery (MSS-5) viewing this same region on 18 July (Figure 2-6) displays areas of overall higher reflectance along the higher ridges of the Lewis Range. The appearance of the terrain is similar to the Sierras in July (Figure 2-1), where subtle differences in reflectance are noted within the overall brighter area. In the corresponding MSS-6 band (red-near IR), shown in Figure 2-7, the areas with subtle differences in reflectance in the visible are seen as distinctly brighter areas. It is likely, therefore, that the Lewis Range contains only partial snow cover. The MSS-6 data are more useful than the MSS-5 for distinguishing the remaining snow from the bare rock surfaces.

2.4 Mid-West

Under the initial study, it was possible to examine only a small part of the large volume of ERTS imagery received over the flatter terrain areas of the Mid-west, particularly the Upper Mississippi-Missouri River Basins region in the north-central part of the country. In the supplemental study further data analysis of this region has been carried out. The results of the analysis of imagery from the 1973 winter and spring seasons has revealed a number of important features, including: (1) variations in reflectance with snow depth; (2) rapid snowmelt; (3) the enhancement of geological features (Nebraska Sand Hills) with snow on the ground; (4) the minimum amount of snow accumulation that can be detected in ERTS imagery; (5) the effect of snow

cover on the genesis of convective clouds; and (6) possible errors in ground truth reports of snow depth.

2.4.1 Brightness vs. Snow Depth

Whereas a single ERTS image is usually sufficient for determining snow cover extent on most individual mountain ranges, the rather limited areal coverage of a single ERTS image does not provide sufficient information to allow mapping of areal snow extent for the larger river basin areas of the Mid-west. The side-lap provided on successive ERTS passes, assuming cloud-free conditions persist, can be utilized to prepare mosaics which provide the overall coverage required to map snow cover over flatter terrain regions. Figure 2-8 shows mosaicked MSS-5 ($0.6-0.7 \mu m$) visible imagery viewing part of the Upper Mississippi River Basin on 8, 9 and 10 February 1973.

The area covered in the mosaic is essentially non-forested, so that the variation in reflectance can be attributed to the amount of snow on the ground. The reported snow depths substantiate this. The mosaic shows an area of little or no snow in southern Minnesota (upper left) immediately adjacent to a brighter band of deeper snow (13-18 cm) extending from southeastern Minnesota southwestward into northwestern Iowa. A lower reflectance is evident just to the east of the brighter band, where depths of only 3-5 cm are reported. The numerous rivers within this region stand out particularly well, even within the band of deeper snow, primarily due to the denser vegetation generally existing along most river banks.

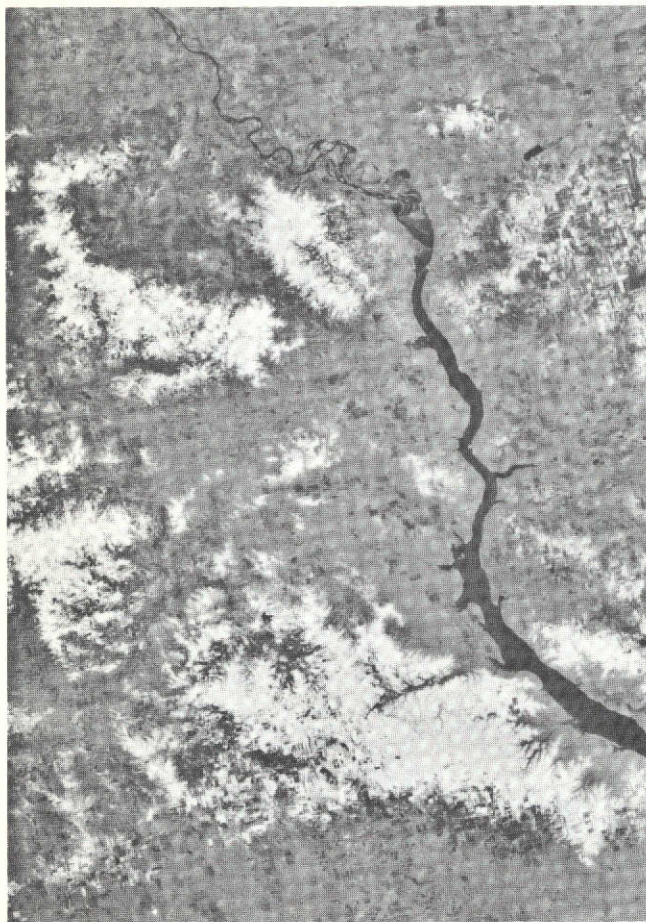
2.4.2 Rapid Snow Melt

Comparison of ERTS images of 9 and 10 April 1973 (Figures 2-9a and 9b) viewing isolated patches of snow cover adjacent to the Missouri River in south central North Dakota indicates an obvious reduction in the areal extent of the snow over the one day period (measurements using a planimeter showed that slightly over 50% of the snow cover disappeared). Based on the brightness of the snow patterns and the amount of observed snow cover decrease, as well as the amount of snow-melt that would be anticipated with the relatively low maximum

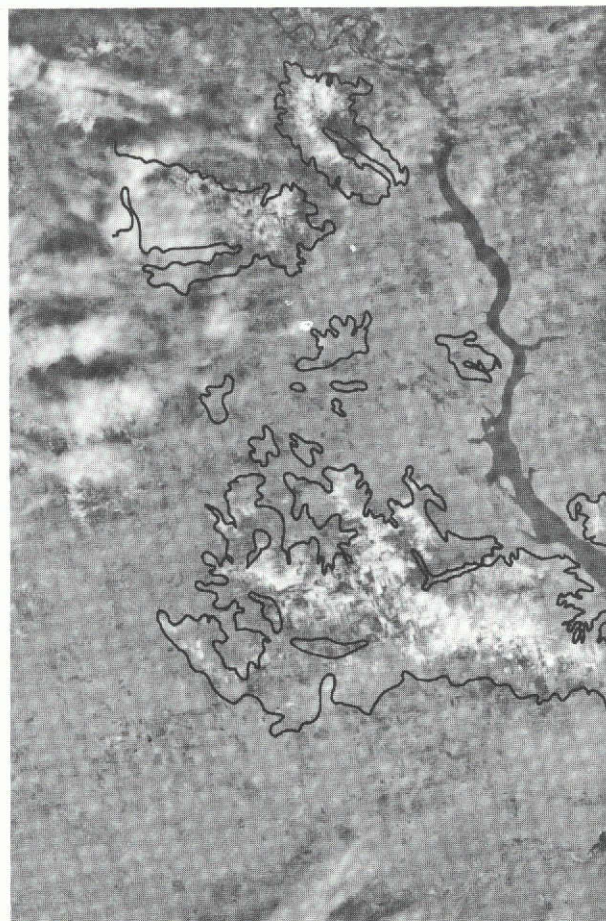


Figure 2-8 ERTS-1 MSS-5 mosaicked imagery of 8, 9, and 10 February 1973, showing a portion of the Upper Mississippi River Basin. An area of little or no snow in southern Minnesota is observed adjacent to a brighter band of deeper snow ranging from 5-7 inches (13-18 cm).

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(a)



(b)

Figure 2-9 Portions of ERTS-1 MSS-5 images of 9 April 1973 (ID No. 1260-17013) and 10 April 1973 (ID No. 1261-17071) showing reduction in areal extent of isolated patches of snow cover near the Missouri River in south central North Dakota. The outline shown on the 10 April image (right) depicts the snow boundary observed on 9 April (left).

temperatures (5 to 8°C) reported over this area during this time, it is deduced that snow depths of from 2 cm (outer limits) to at least 7 cm (central portions) likely existed on the 9th. Examination of available ground truth reports showed that the network of reporting stations in this region is not dense enough to reveal the existence of the limited areas of snow cover.

2.4.3 Nebraska Sand Hills

The enhancement of geological features when snow is on the ground is illustrated in MSS-5 imagery of 9 January 1973 (Figure 2-10) viewing the Sand Hills region of western Nebraska. This region covers approximately 22,000 square miles, more than one-fourth of the area of the state, and is an area of presently stabilized dunes or lag deposits covered by sod (Smith, 1965). If this present sod cover were destroyed and the Sand Hills reactivated, this area would be comparable to the great dune fields of the Sahara (Thornburg, 1969).

The irregular topography of the Sand Hills region is not evident in ERTS images viewing the region when it is snow-free. On 9 January however, the snow cover provides a uniform background, covering vegetation and cultural features that tend otherwise to obscure the geological structure of the terrain. At the same time, a relatively low sun angle (21°) at an azimuth of 152° allows illumination of only the south sides of the nearly east-west oriented Sand Hills, while the north sides remain in shadow. The resulting enhancement of this geological feature with snow cover creates a non-uniform texture that closely resembles a stratocumulus cloud layer.

2.4.4 Effect of Snow Cover on Cloud Formation

Isolated patches of snow cover comprised of insignificant depths can apparently prevent the formation of low level convective cloud layers. An ERTS MSS-5 image of 4 March 1973 (Figure 2-11) viewing the area of northeast Colorado, shows a band of snow approximately 100 km long and 25 to 30 km wide located immediately south of the South Platte River. Reported snow depths are only about 3-5 cm, but even this amount is apparently sufficient to prevent the formation

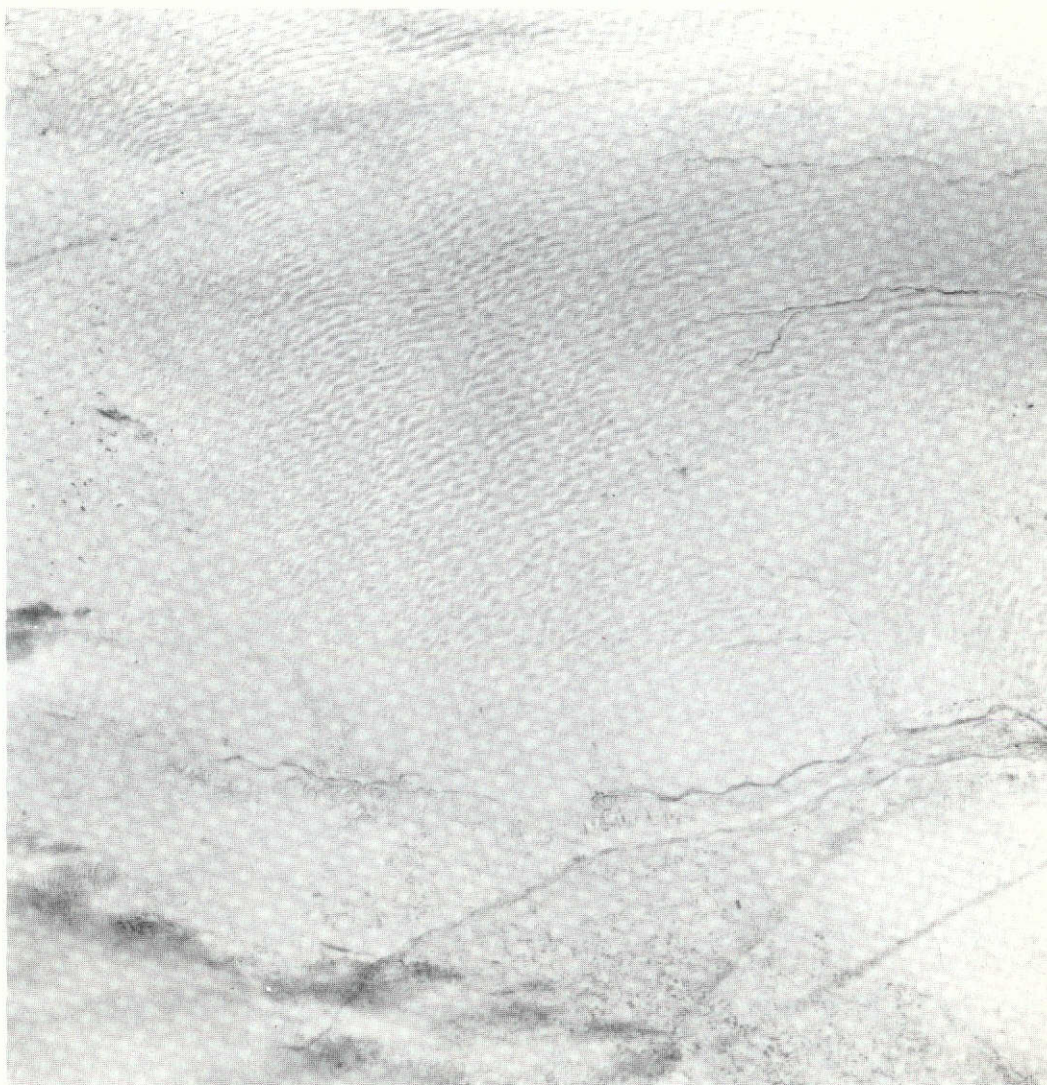


Figure 2-10 ERTS-1 MSS-5 image (ID No. 1170-17020) showing the Nebraska Sand Hills region with snow on the ground, 9 January 1973. The resulting enhancement of this geological feature with snow cover creates a non-uniform reflectance that closely resembles a strato-cumulus cloud layer.

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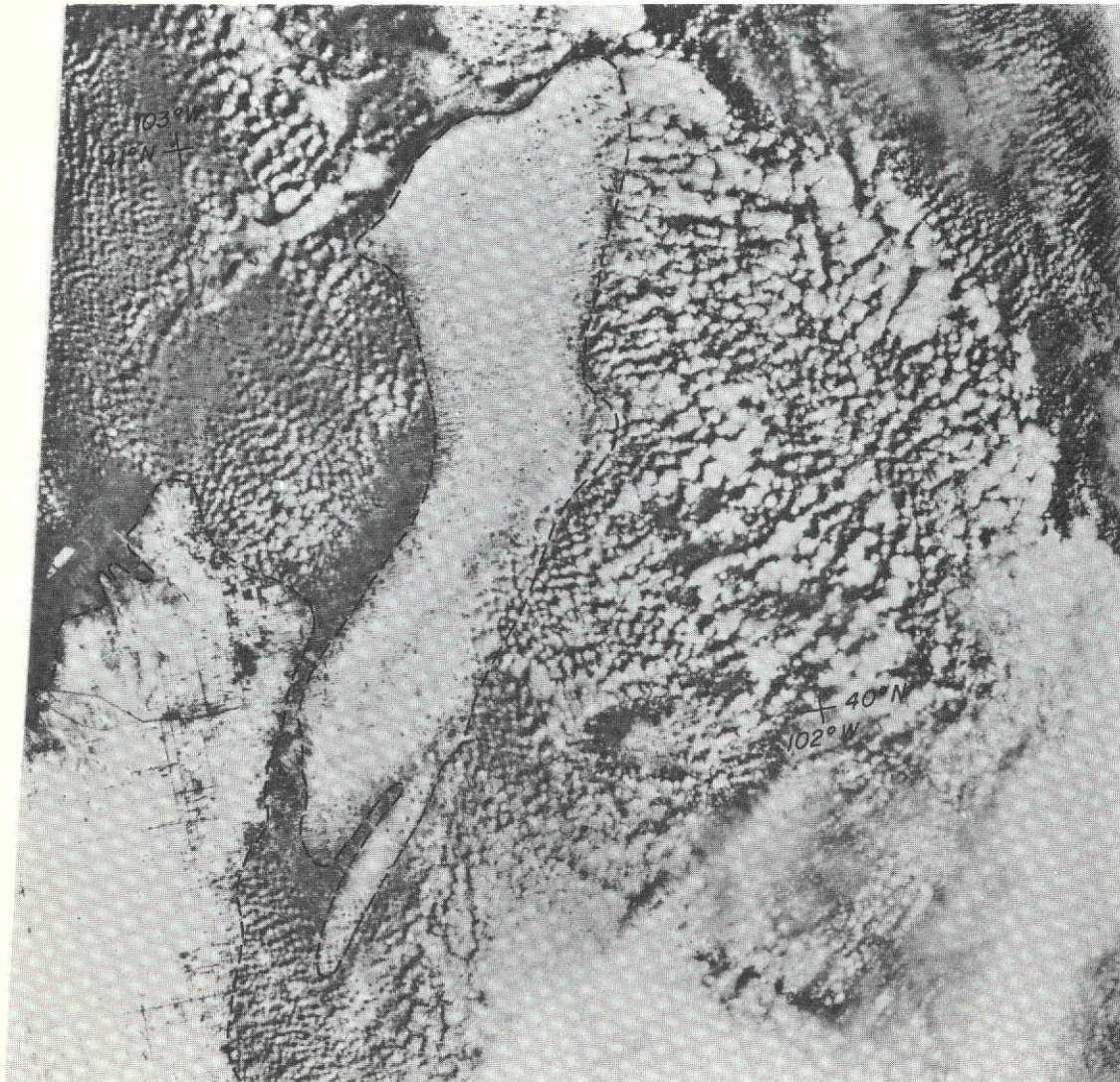


Figure 2-11 ERTS-1 MSS-5 image (ID No. 1224-17030) showing low level convective clouds over snow-free terrain in northeast Colorado, whereas patches of snow cover appear generally cloud-free, 4 March 1973. The snow boundaries are indicated by a dashed line.

of convective cloudiness, which is observed forming over the surrounding, snow-free terrain due to heating of the ground surface. Similarly, a portion of another patch of snow cover located to the south and west also appears mostly cloud-free.

2.4.5 Minimum Detectable Snow Depth

Snow patterns mapped from a number of ERTS images viewing non-forested, relatively flat terrain areas of the Mid-west were compared with corresponding snow depth reports. The comparison has shown a good correlation between brightness and snow depth for lesser snow amounts. In general, accumulations of less than about 7 cm are observed at distinctly lower or less uniform reflectances than are greater snow depths. However, even a Trace of snow can, in most instances, be detected. Snow amounts of from 2 to about 7 cm, although having a higher reflectance than amounts from a Trace to 2 cm, are often non-uniform in brightness especially in areas where agricultural activities (plowed field, vegetation, grass) remain visible. An ERTS MSS-5 image of 17 March 1973, viewing north-central Iowa and southern Minnesota (Figure 2-12), displays numerous relatively bright streaks; two stations in the area report a Trace of snow on the ground. Surface weather charts indicate that snow squalls had passed over this area during the previous day.

2.4.6 Apparent Discrepancies in Reported Snow Depths

In some instances, reports of snow depth listed in the Climatological Data booklets published by the U. S. Dept. of Commerce (NOAA) appear to be questionable when compared to snow cover reflectances observed in ERTS data. For example, mosaicked MSS-5 images of 10 April 1973 (Figure 2-13) show extensive snow cover in an area east of Denver, Colorado. Two stations within the area of maximum reflectance report accumulations of from 10 to 14 cm, whereas two other stations (Byers and Parker, Colo.) also within the area of maximum brightness are reporting only a Trace. Additional reports of a Trace of snow cover are located immediately south of the zone of maximum brightness in an area of obviously greyer tone.

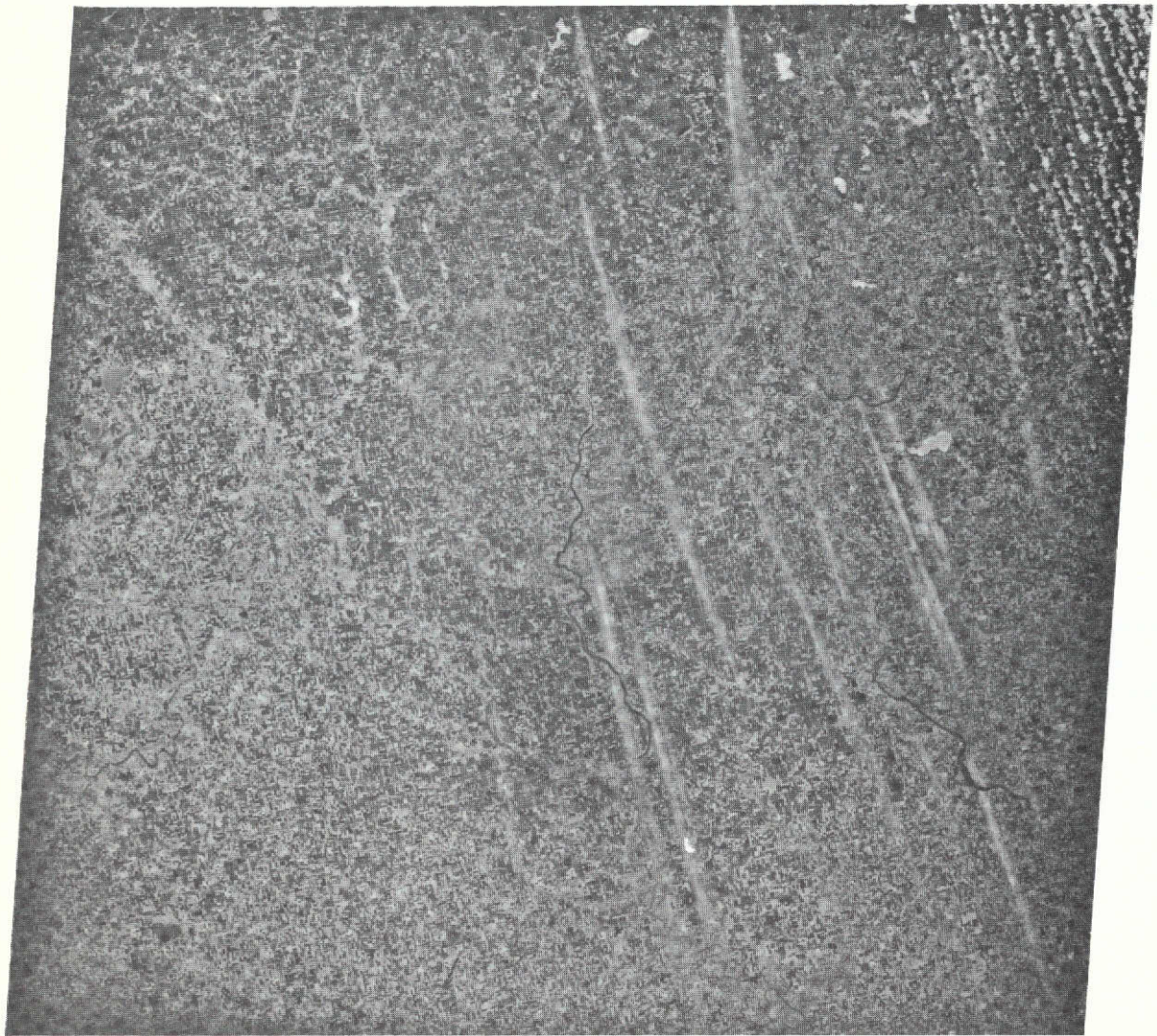


Figure 2-12 ERTS-1 MSS-5 image (ID No. 1237-16333) showing north-central Iowa and southern Minnesota, 17 March 1973. Snow cover consists of relatively bright streaks resulting from reported snow squalls over this region on the previous day. Two stations in the area report a Trace of snow on the ground.

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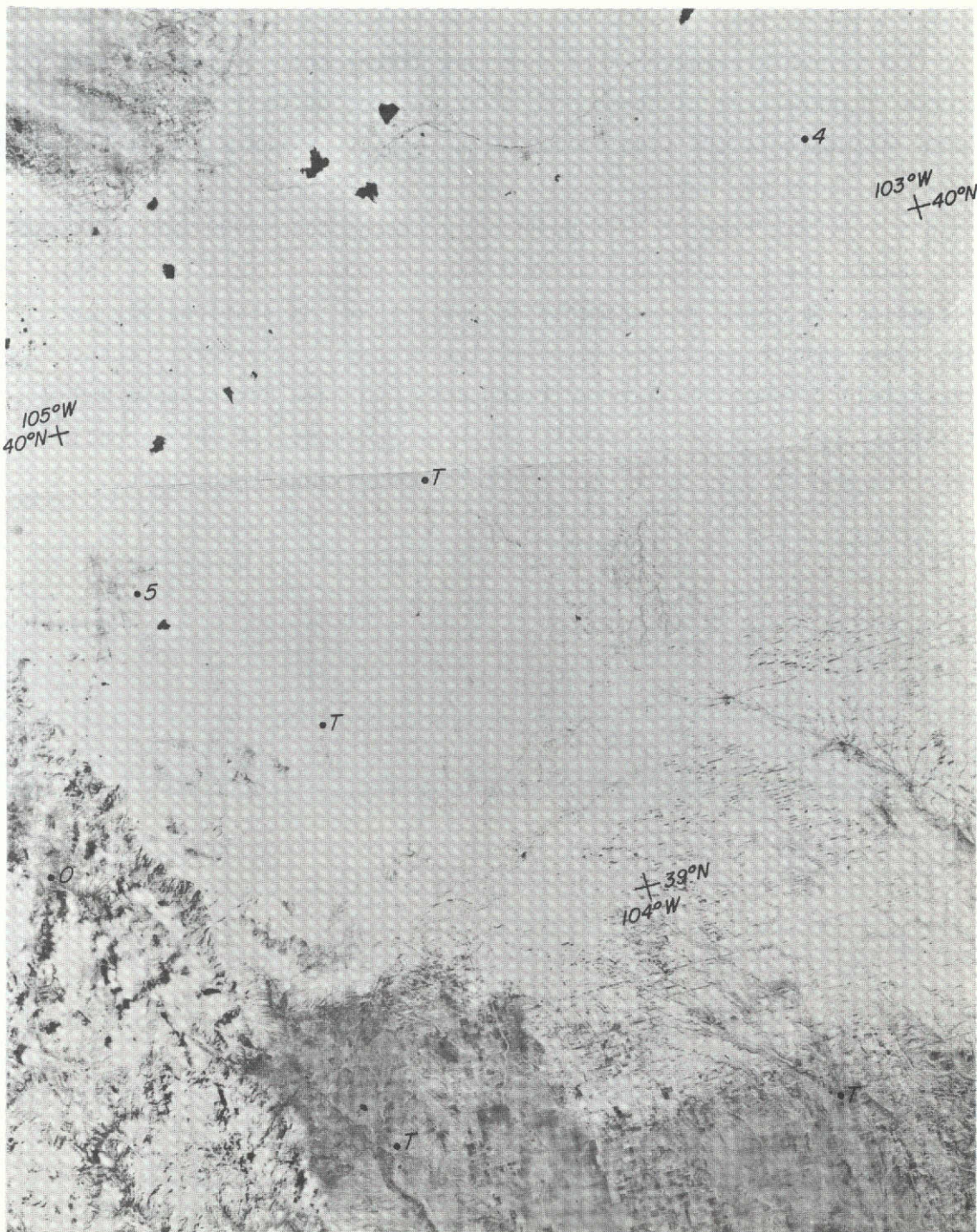


Figure 2-13 ERTS-1 MSS-5 mosaic (ID Nos. 1261-17085 and 1261-17091) showing extensive snow cover east of Denver, Colorado, 10 April 1973. Two reporting stations within the area of maximum reflectance report accumulations of 4 to 5 inches (10-14 cm), whereas two other stations (Byers and Parker, Colorado) also within the area of maximum brightness are reporting only a Trace.

The interpretation of this apparent discrepancy, based on reported maximum temperatures of about 7°C on this date, as well as the significant snowmelt in the area observed in imagery of the following day, is that a Trace may have existed at Byers and Parker much later in the day. At the time of ERTS passage (approximately 1000 LST), however, more than a Trace was likely present on the ground. This broad range of contrast in depth measurements suggests that the stations may not take their measurements at the same time of day. In order to obtain meaningful correlations between brightness and snow depth, especially during periods of rapid snowmelt, depth measurements at corresponding times throughout the reporting network is an obvious requirement.

3. COMPARISON OF 1973 and 1974 WINTER DATA

3.1 Sierra Nevada

Comparison of ERTS MSS-5 images of 25 February 1973 and 2 February 1974 (Figures 3-1 and 3-2) viewing the area of the Sierras from Mono Lake southward, reveals that the overall snow lines are of about equal extent. In fact, the only obvious differences appear in the lower elevations immediately surrounding Mono Lake and the northern extent of Owens Valley where snow cover, observed in 1973, is not present in 1974. The overall extent of maximum brightness, which is restricted to the higher elevation terrain above the timber line, also appears identical. Analysis of snow course data, however, indicates that differences did exist in the snowpack volume, which are not obvious in the imagery. The 1973 snowpack was reported to be 75-100 cm greater in the San Joaquin and Kings River Basins and approximately 120 cm greater in the Kaweah, Tule and Kern Basins.

ERTS color composite data have the unique advantage of allowing positive identification of forested areas, which appear in varying tones of red depending upon the density and type of vegetation. A comparison of an ERTS color composite viewing this same region on 16 September 1972 with the image of February 1973 clearly shows the effect of heavily forested terrain on snow cover reflectance. Mapping of the forest boundaries from the color composite image and overlaying them on the image of February 1973 show close agreement between the pattern of non-forested rock surfaces at higher elevations and the pattern of maximum reflectance when the Sierras are snow covered. Moreover, the mottled appearance (alternating dark-bright) is restricted to the heavily forested lower elevation terrain. Although the actual snow line falls within the darker forested terrain area, it appears easily identifiable.

3.2 Salt-Verde Watershed - Arizona

In contrast to the southern Sierras, a significant difference in the snow extent over a portion of the Salt-Verde Watershed is observed in ERTS images of 14 January 1973 and 27 January 1974 (Figures 3-3 and



Figure 3-1

ERTS-1 MSS-5 imagery (ID No. 1217-18065) viewing the southern Sierras on 25 February 1973. The overall extent of maximum brightness is restricted to the higher elevation non-forested terrain (NF) above the densely forested lower elevation terrain (F) where the reflectance is alternating dark-bright.

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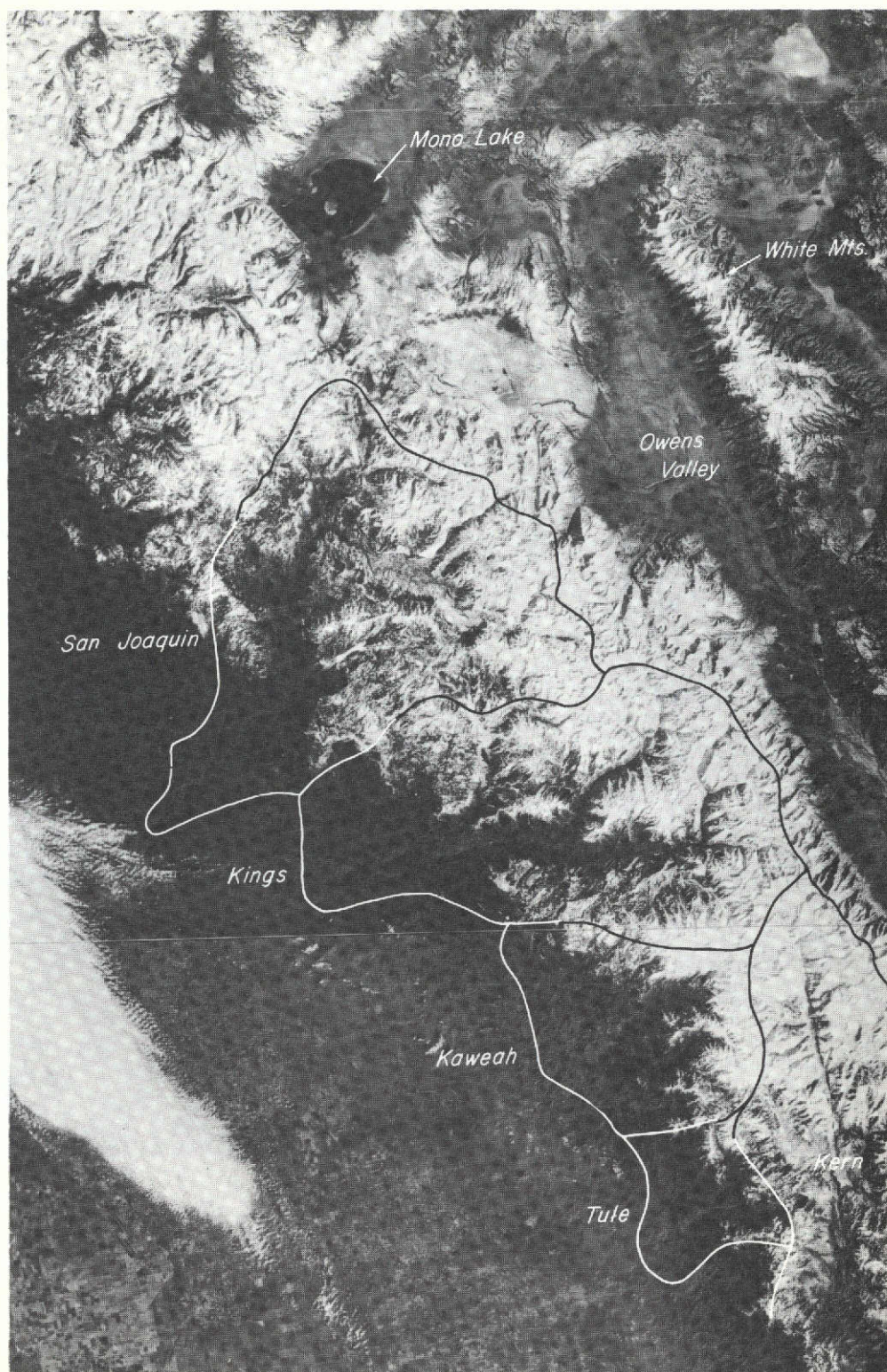


Figure 3-2

ERTS-1 MSS-5 imagery (ID No. 1559-18020) viewing the southern Sierras on 2 February 1974. The areal extent of snow cover appears about equal to that observed in the February 1973 image (previous figure) except in the lower elevations immediately surrounding Mono Lake and the northern extent of Owens Valley. The boundaries of the San Joaquin, Kings, Kaweah, Tule and Kern River Basins are indicated.

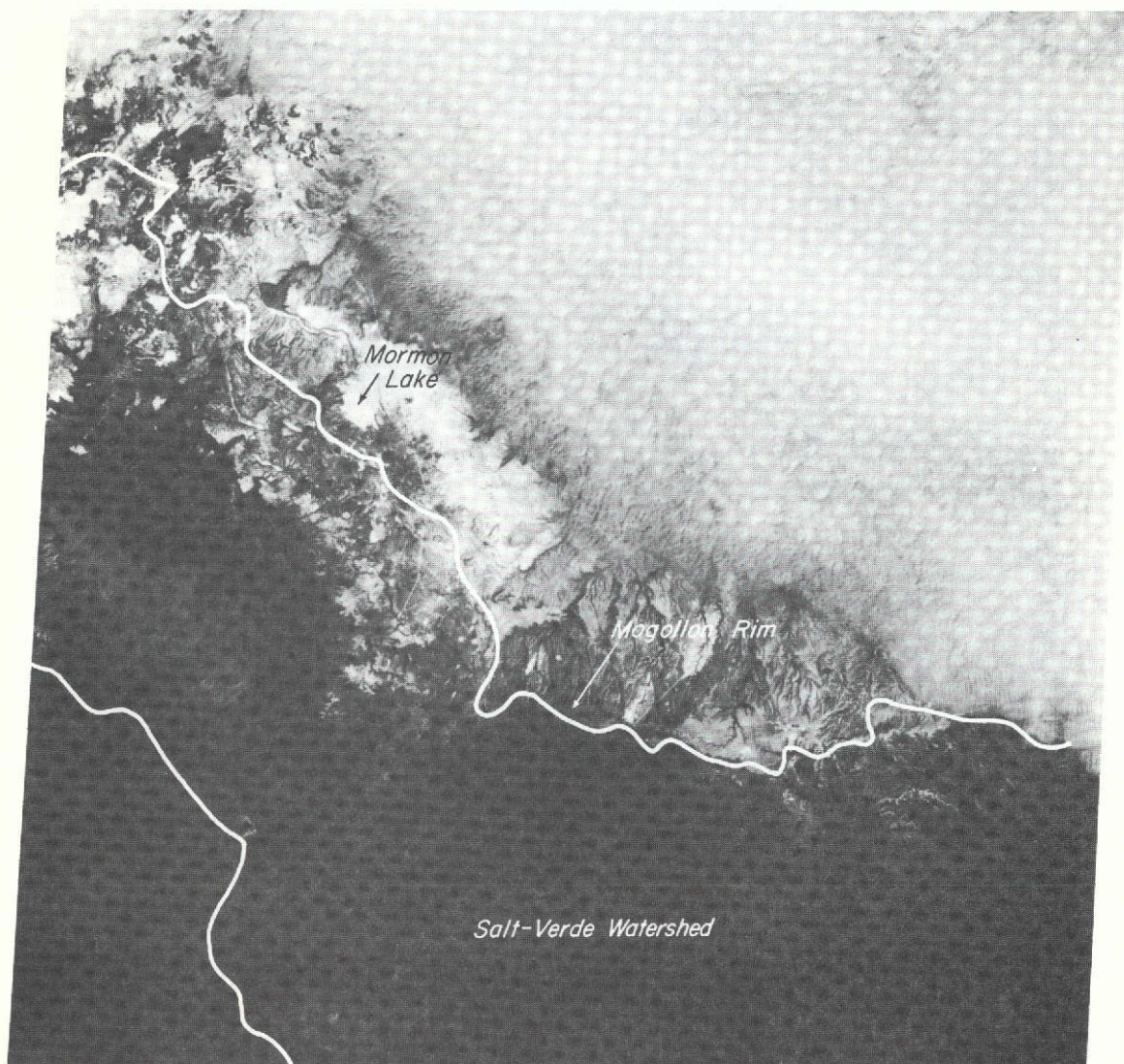


Figure 3-3 ERTS-1 MSS-5 image (ID No. 1175-17324) showing a portion of the Salt-Verde Watershed, 14 January 1973. The watershed boundary, Mogollon Rim and Mormon Lake are indicated. Clouds cover the area northeast of the mountains.

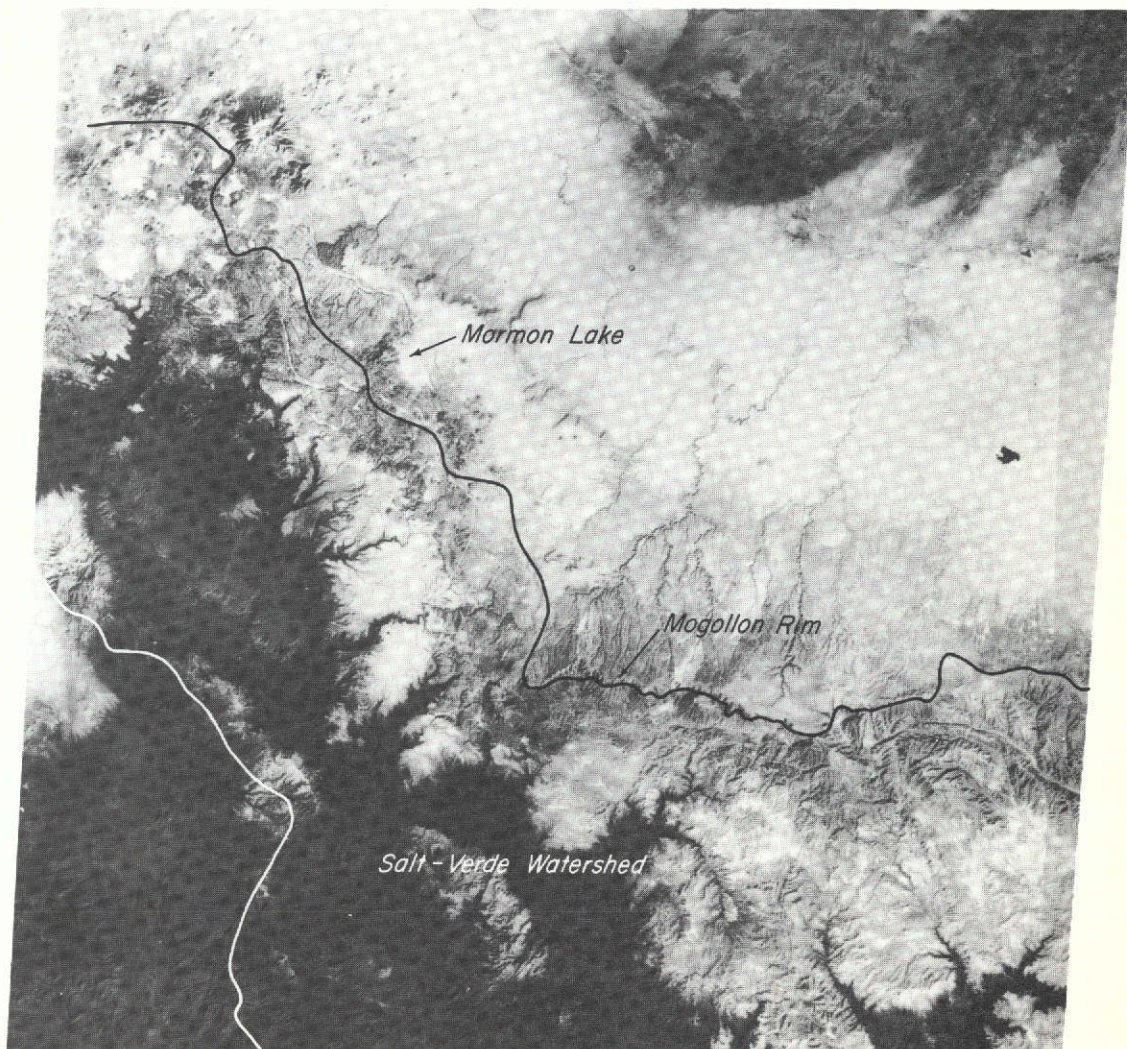


Figure 3-4 ERTS-1 MSS-5 image (ID No. 1553-17284) showing a portion of the Salt-Verde Watershed, 27 January 1974. Note the overall greater areal extent of snow cover and increased reflectance than observed in the January 1973 image (previous figure). The watershed boundary, Mogollon Rim and Mormon Lake are indicated.

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3-4). In January 1973, the areal extent of snow cover does not extend south of the Mogollon Rim, whereas in the 1974 image snow is apparent over much of the terrain to the south. Moreover, flat-topped mesas just west of the Mogollon Rim that are identifiable because of high reflectance due to snow cover in the 1974 image, are not observed in the 1973 image. Further, the lower overall reflectance of the snow cover on the earlier date clearly suggests significantly lower snow depths. Corresponding aerial survey snow charts provided by the state of Arizona reported that accumulations were as much as 30 cm greater in mid-January 1974.

4. COMPARISON WITH SKYLAB AND AERIAL PHOTOGRAPHY

To facilitate comparison of ERTS imagery with Skylab and aerial photography, the various types of data are shown for the same geographic area during the same month of the year, January 1974. The area covered is the central Arizona mountains, an area where snow hydrology is a vital consideration. Although the snowpack in central Arizona is small in comparison with that of areas such as the Sierra Nevada or Cascades, it is still the major source of surface runoff in the State of Arizona (Warskow, 1971). Moreover, accurate monitoring of the Arizona snowpack is required because it is extremely variable from year to year, and rapid snowmelt can occur at lower elevation areas at anytime during the snow season.

A map of Arizona with the Salt-Verde Watershed indicated is shown in Figure 4-1. Elevation contours show that maximum elevations in this area are of the order of 2000-2500 meters (7000-8500 feet).

4.1 Aerial Photography

Aerial photography taken over central Arizona on 15 January 1974 as part of the NASA Earth Resources Aircraft Program (ERAP) is shown in Figure 4-2. The black and white mosaic is reproduced from the original S0397 color photography that was taken by an RB-57 aircraft using an RC-8 camera. In the aerial photography ice covered Mormon Lake is visible near the center; the dark band just north of the lake is Ashurst Run and the straight, white line is a power-transmission line swath. The open snow covered land appears very bright, whereas the forested land, although also snow-covered, appears in various shades of grey. The boundary of the snowpack is at the lowermost portion of the mosaic. The area covered by the aircraft photograph is outlined on each of the sample images discussed in the following paragraphs.

4.2 Skylab-S190A Photography

A considerable amount of photography over snow covered areas within the United States was collected on the Skylab missions, both as part of the EREP (Earth Resources Experiment Package) Project and the

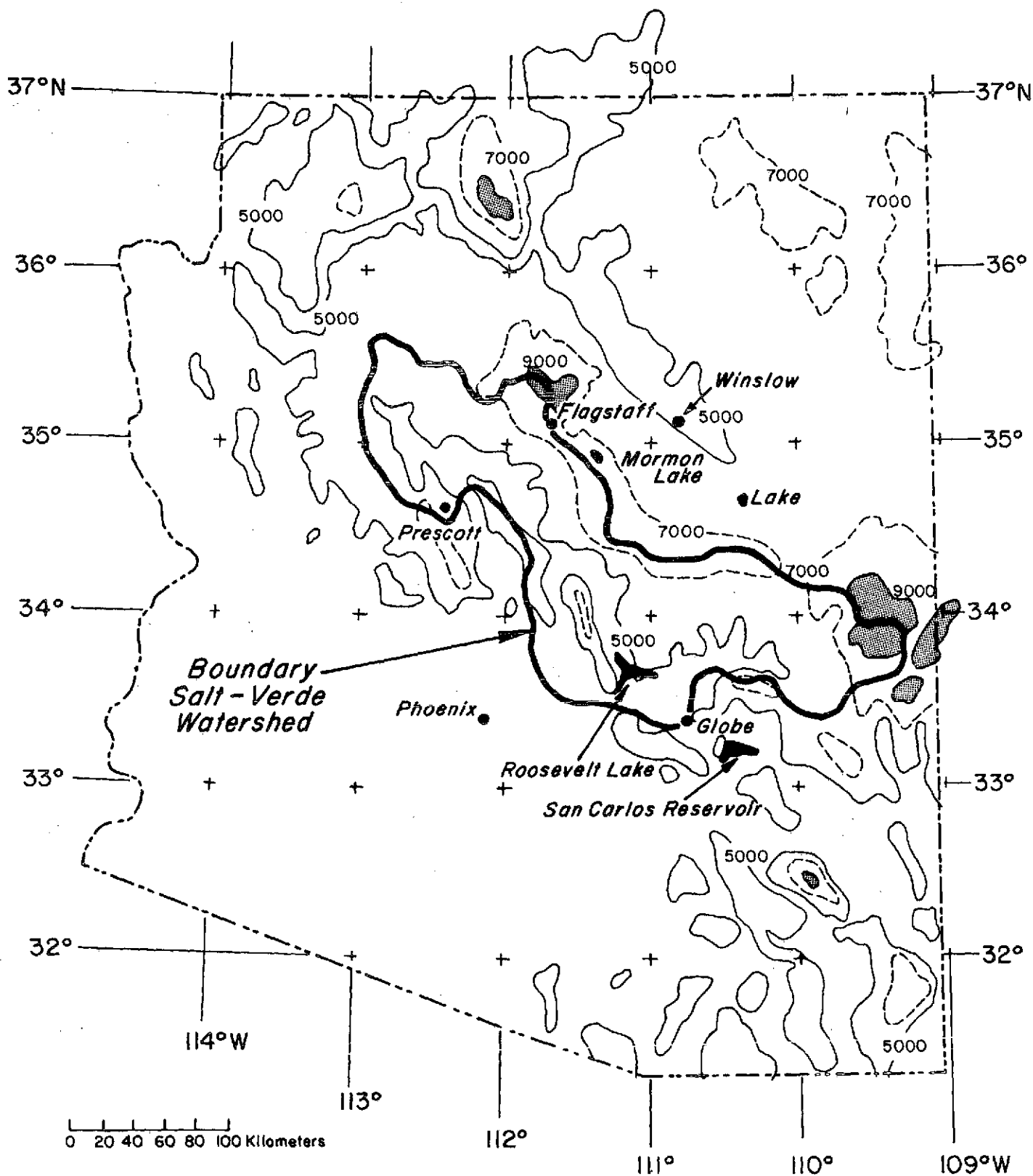


Figure 4-1 Map showing Salt-Verde Watershed, Arizona test site. Contours for 1500 m (5000 ft.), 2100 m (7000 ft.), and 2700 m (9000 ft.) are indicated.



Figure 4-2 Aerial mosaic viewing central Arizona on 15 January 1974. The following features are indicated: Mormon Lake (A), Ashurst Run (B), power-transmission line swath (C), and Stoneman Lake (D).

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Skylab-4 Visual Observations Project. Although these data were not intended for operational snow mapping use, the cameras did provide photographs with higher resolutions than even the data from ERTS.

A Skylab-4 S190A photograph taken on an EREP pass across central Arizona on 14 January 1974 is shown in Figure 4-3. The S190A is a six-camera multispectral system with a resolution of 30-70 meters; the photograph shown is in the visible spectral region. The boundary of the snowpack is readily apparent, as are the variations in reflectance due to dense forest cover. Mormon Lake, Ashurst Run, and the power-transmission swath noted on the aerial mosaic are also easily identified. A map showing the snow extent derived from a Skylab handheld photograph and as depicted by the Salt River Project Office on their aerial survey chart of the following day is given in Figure 4-4. Snow depth estimates made from the aerial survey (through visual sightings of markers and other indicators) are also plotted.

4.3 ERTS MSS

The date of the nearest correlative ERTS-1 data covering central Arizona was on 27 January 1974. The ERTS image on that date, which was also discussed in Section 3-2, is shown in Figure 4-5. Although this image reveals significantly greater overall snow extent within the Salt-Verde Watershed to the south of the Mogollon Rim and north of the watershed toward the desert region, only slight differences are observed within the area shown in the aerial photograph (Figure 4-2). The widespread snowfall of 5-10 cm that occurred early on the 27th resulted in only a slight southward progression of the snow extent into forested terrain located south of the higher reflecting flat-topped mesas previously observed as the southern snow extent. Moreover, the comparison of this area as depicted in the ERTS image with the features noted in the aerial and Skylab photographs, reveals that Mormon Lake, Ashurst Run and the power-transmission swath, as well as forested (lower reflectance) vs. non-forested (maximum reflectance) terrain are easily identifiable. In fact, it does not appear that the resolution of the S190A photograph or even that of the aerial photograph provide any significant improvement over the ERTS resolution with regard to mapping overall snow extent.

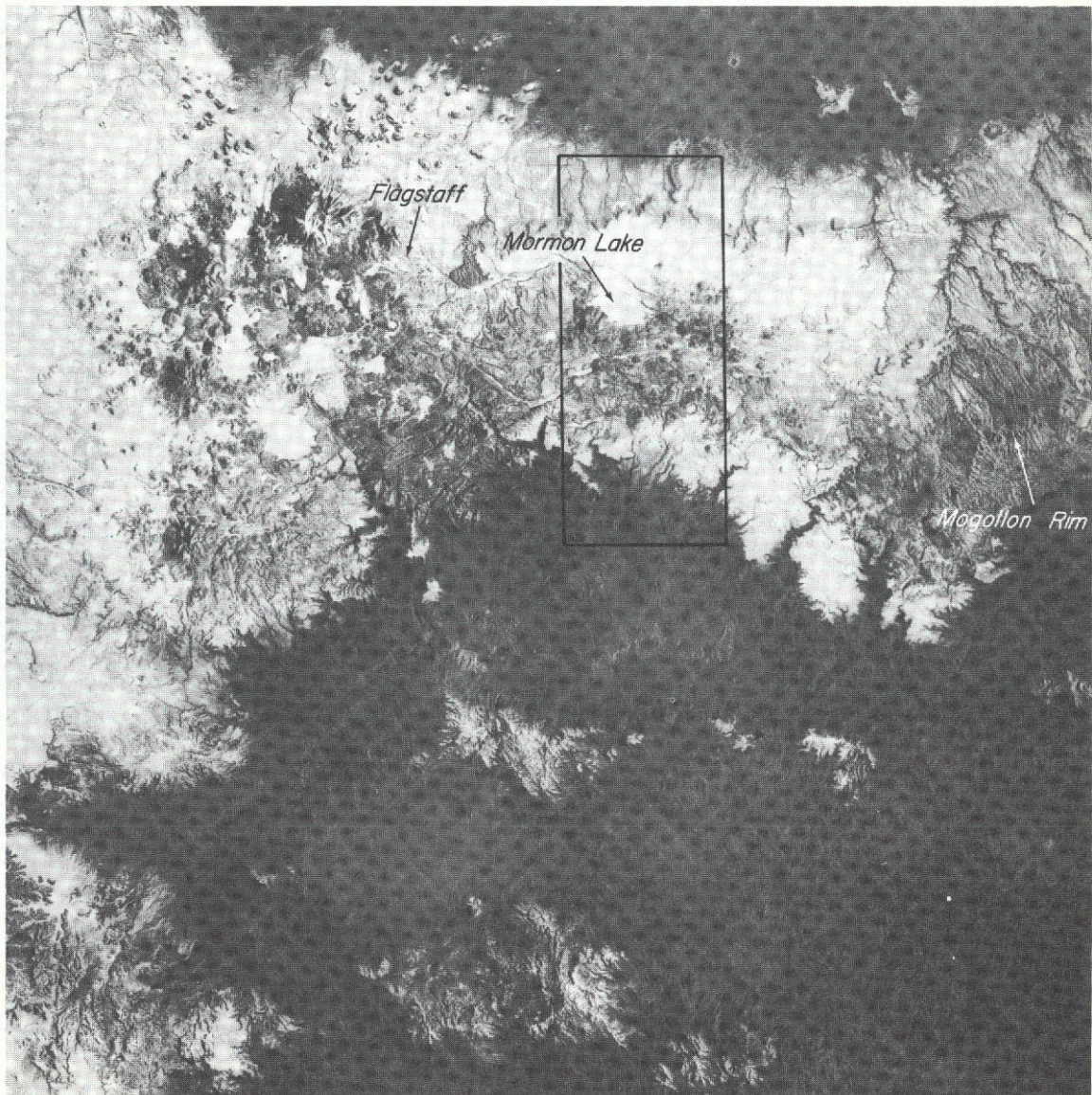


Figure 4-3 Skylab-4 S190A Camera Station 6 (0.5-0.6 μm) photograph viewing central Arizona on 14 January 1974. The area shown in the aerial photography (previous figure) is outlined.

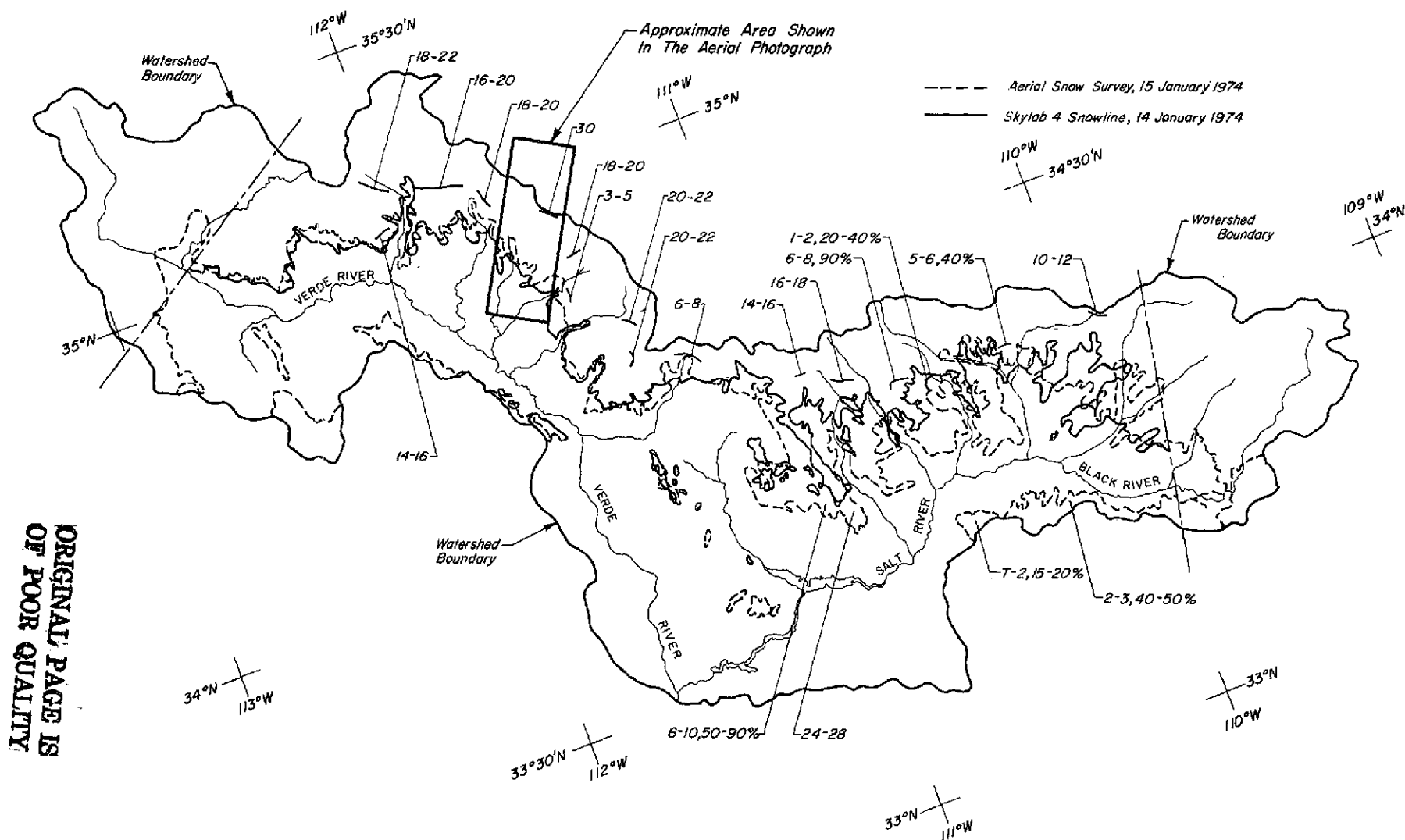


Figure 4-4

Map of Salt-Verde Watershed showing snowlines mapped from Skylab handheld photograph of 14 January (solid line) and depicted on aerial survey snow chart of 15 January 1974 (dashed line). Snow depth (in inches), percentage of area with snow cover, and area shown in aerial photograph (Figure 4-2) are indicated.

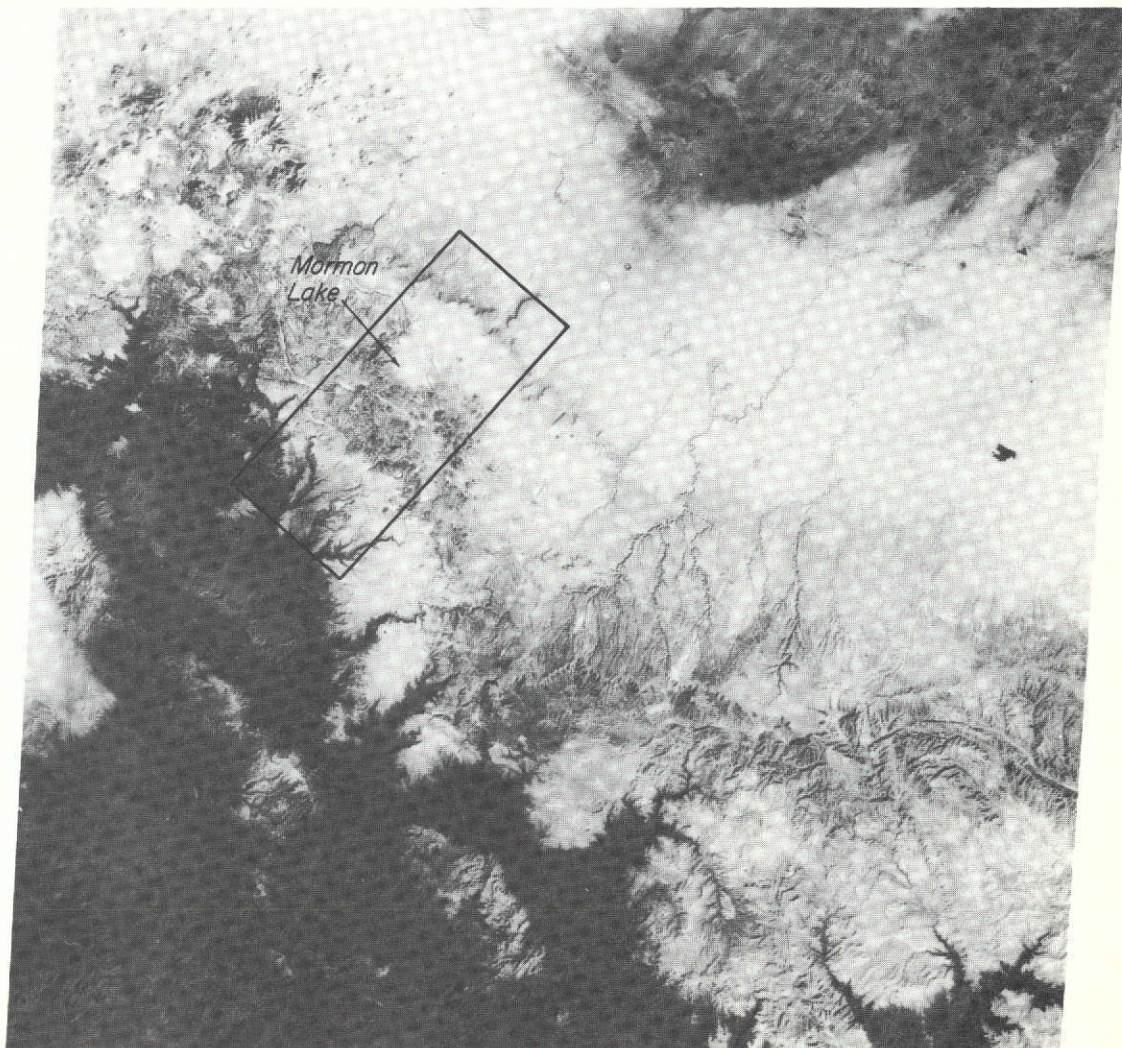


Figure 4-5 ERTS-1 MSS-5 image (ID No. 1553-17284) showing a portion of the Salt-Verde Watershed, 27 January 1974. The area shown in the aerial photography (Figure 4-2) is outlined.

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5. CORRELATION BETWEEN SNOW EXTENT AND RUNOFF

Until recently, snow studies using satellite data have concentrated on the development of techniques for identification and mapping. However, a sufficient accumulation of high resolution ERTS data now exists, so that studies of the relationships between satellite-viewed snow extent and runoff can be undertaken. Preliminary relationships between the average snow cover depletion determined from ERTS observations and runoff curves for drainage basins in the Wind River Range in Wyoming have been reported by Rango and Salomonson (1974).

The percentage of snow cover for each of the four southern Sierras river basins (Kings, Kaweah, Tule and Kern) during the 1973 spring season determined from a number of ERTS MSS-5 images is shown in Figure 5-1. The actual runoff data (thousand acre feet) for the same period obtained from the State of California, Department of Water Resources, are also plotted. The resulting graphs show that the greatest runoff, by far, is in the Kings Basin. Even though the runoff values are only the monthly totals, the relationship for the Kings Basin is similar to the results obtained by Rango and Salomonson for the Wyoming drainage basins.

Although good correlations are observed between periods of increased runoff and snow cover depletion, some periods of a greater snow cover depletion have reported lesser amounts of runoff. For instance, a depletion of about 20% of snow cover for the Kings Basin during May, corresponded to runoff of 748,000 acre feet, while during June, a depletion of approximately 30% resulted in runoff of only 555,000 acre feet. This suggests that much of the runoff during May could have been the result of locally heavy rainfall during this period at lower elevations rather than actual snowmelt. Or, it may be that during May the entire snowpack is decreasing in volume even though the decrease in actual snow extent amounted to only 20%; during June, the snow depths are considerably less to begin with, so that further melting causes a more dramatic decrease in the snowpack extent.

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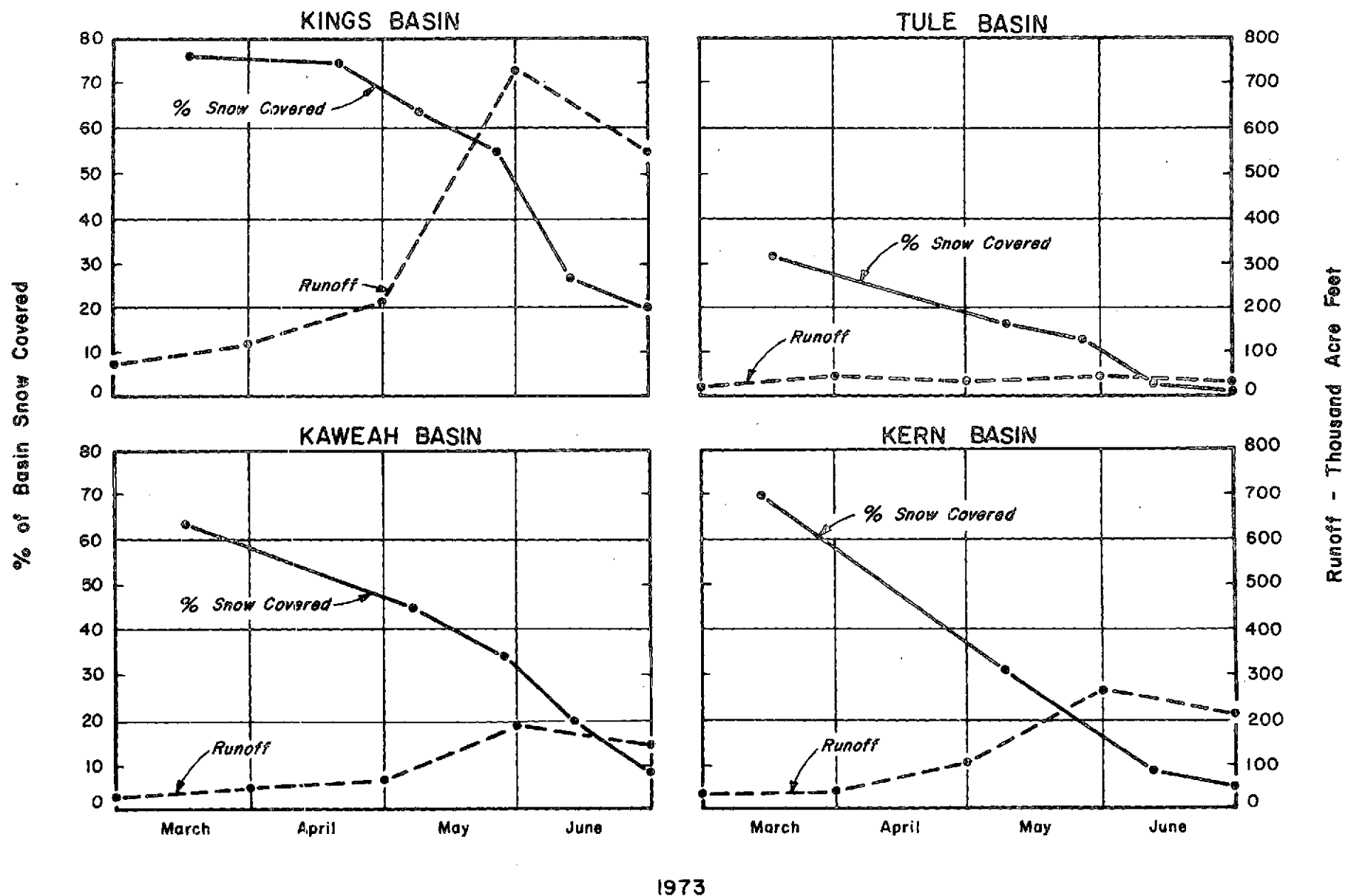


Figure 5-1

Snow extent in four southern Sierra Nevada river basins mapped from ERTS data and actual runoff data for spring 1973. Snow extent is in percent of basin snow covered and runoff values are in thousand acre feet.

6. SUMMARY OF RESULTS

Analysis of additional ERTS imagery of summer 1973 has shown that limited snow cover confined to the higher elevation ridges and peaks of the southern Sierras can be identified by its uniform texture and higher reflectance when compared with observations taken during late summer and early fall. The analysis of summertime data has also provided additional examples of wet, melting snow surfaces having a lower reflectance in the near-IR (MSS-7) imagery than in the visible. In one instance, it appears that the extent of the glaciers in the Cascades in Oregon can be mapped using the near-IR data. Although some useful data for the Upper Columbia Basin were obtained, cloud obscuration remains a severe problem in that region.

Comparison of snow cover distributions of the southern Sierras and central Arizona mountains observed during corresponding wintertime periods of 1973 and 1974 indicates that even relatively small differences in areal snow extent are easily detected. However, a major difference in the depth of the snowpack in the Sierras (up to 120 cm) was not discernable in the ERTS imagery. Also, mapping of forested terrain in the southern Sierras, as determined by analysis of ERTS color composite imagery of late summer, has shown excellent correlation with the areas displaying a mottled (alternating dark-bright) reflectance during periods of maximum snow cover; the non-forested, higher elevation terrain displays a greater and more uniform overall reflectance.

Analysis of a number of ERTS images viewing snow cover over the flatter terrain areas of the Mid-west during the 1973 winter and spring seasons has revealed a number of significant findings, including:

- (1) the combination of low sun angle and snow on the ground greatly enhances geological features, such as the Sand Hills of Nebraska;
- (2) small snow covered areas that can be mapped from ERTS may be missed completely by the network of reporting ground stations;
- (3) variations in the reflectance of lesser amounts of snow can frequently be attributed to varying snow depths;
- (4) snow amounts as small as a reported Trace of snow are usually detectable in the ERTS imagery;
- (5) the existence of even patchy, insignificant snow accumulations may impede the formation of low level convective clouds;
- (6) the sidelap provided by ERTS passes

on successive days allows detection of rapid reductions in the areal extent of snow cover during the melting season; and (7) the observed reflectances of snow cover in ERTS imagery indicates that in some instances apparent discrepancies exist in reported snow depths. These discrepancies may arise because the stations do not take their measurements at the same time of day.

Additional comparisons of the ERTS data with high-altitude aircraft, as well as Skylab, photography have provided further evidence that major features including boundaries of the areas of significant snow cover can be mapped as accurately from the ERTS imagery as from the higher resolution data.

A comparative analysis of the snow cover depletion of four southern Sierras river basins (Kings, Kaweah, Tule, and Kern) with actual runoff data during the 1973 spring season has shown good correlation during the period of maximum runoff. The results are similar to those obtained by other investigators for drainage basins in the Wind River Range in Wyoming.

These additional analyses further substantiate the application of ERTS for detecting and mapping snow cover. Sufficient ERTS data have now been accumulated to enable extensive studies to be undertaken to determine the relationships between average snow cover depletion and runoff curves, as well as year to year variations in the extent of major mountain snow packs. Also, detailed studies of the multispectral snow signatures using ERTS digitized data have yet to be accomplished. Such studies are needed to gain a proper understanding of the quantitative relationships between the variations in reflectance observed in the imagery and the snow conditions and between reflectance and snow depth. Studies of the digitized data are also needed to develop automated processing techniques for eventual use in operational snow cover monitoring programs.

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